

# Origin of Intense Magnetic Fields Near Neutron Stars and Black Holes Due to Non-Minimal Gravitational-Electromagnetic Coupling.

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## Abstract

The origin of magnetic fields in astrophysical objects is a challenging problem in astrophysics. Throughout the years, many scientists have suggested that non-minimal gravitational-electromagnetic coupling (NMGEC) could be the origin of the ubiquitous astrophysical magnetic fields. We investigate the possible origin of intense magnetic fields  $\sim 10^{15} - 10^{16}$  by NMGEC near rotating neutron stars and black holes, connected with magnetars, quasars, and gamma-ray bursts. Whereas these intense magnetic fields are difficult to explain astrophysically, we find that they are easily explained by NMGEC.

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## I. INTRODUCTION

Cosmic magnetic fields pervade the Universe. However, their origin is one of the most challenging problems in modern astrophysics (e.g., [1], [2]). Various authors have suggested a gravitational origin of the magnetic fields in rotating celestial bodies. In particular, a number of studies have been made on nonminimal gravitational electromagnetic coupling (NMGEC). It has been motivated, in part, by the Schuster-Blackett (S-B) conjecture, which suggests that the magnetic fields in planets and stars arise due to their rotation [3]. In this scenario, neutral mass currents generate magnetic fields, implying the existence of a non-minimal coupling between gravitational and electromagnetic fields. An early attempt to encompass the S-B conjecture in a gravitational theory was made by Pauli in the 1930s [4]. During the 1940s and 50s, after Blackett resuscitated the conjecture [5], many authors, such as Bennett et al. [6], Papapetrou [7], and Luchak [8], also attempted to encompass it in a gravitational theory. Later, in the eighties, Barut & Gornitz also studied the NMGEC conjecture [9]. The majority of these studies were based on the five-dimensional Kaluza-Klein formalism. This formalism was used in order to describe a unified theory of gravitation and electromagnetism with NMGEC in such a way that the S-B conjecture is obtained. Opher & Wichoski [10] proposed that the  $B \sim 10^{-6} - 10^{-5}$  G magnetic field in spiral galaxies is directly obtained from NMGEC. In this paper, we investigate the possibility that NMGEC is the origin of the intense magnetic fields near rotating neutron stars and black holes, connected with magnetars, quasars, and gamma ray bursts.

## II. BASIC FEATURES OF THE MODEL

NMGEC suggests the following relation between the angular momentum  $\mathbf{L}$  and the magnetic dipole moment  $\mathbf{m}$ :

$$\mathbf{m} = \left[ \beta \frac{\sqrt{G}}{2c} \right] \mathbf{L}, \quad (1)$$

where  $\beta$  is a constant,  $G$  the Newtonian constant of gravitation, and  $c$  is the speed of light. The angular momentum  $\mathbf{L}$  is

$$\mathbf{L} = I\boldsymbol{\Omega}, \quad (2)$$

where  $\mathbf{\Omega} = 2\pi P^{-1}$  is the angular velocity,  $P$  the rotational period, and  $I$  is the moment of inertia. The dipole moment  $\mathbf{m}$  is related to the magnetic field  $\mathbf{B}$  by

$$\mathbf{m} = 1/2r^3\mathbf{B}, \quad (3)$$

where  $r$  is the distance from  $\mathbf{m}$  to the point at which  $\mathbf{B}$  is measured.

Moving electric charges can create an additional magnetic field. This field may partly compensate for the magnetic field of NMGEC origin. If a NMGEC field  $B_{nm}$  is present, the total magnetic induction field  $B_{tot}$  is  $B_{tot} = B_{nm} + B_{em}$ , where  $B_{em}$  is the magnetic field induced by the moving charges.

Since electric charges may move in different ways in rotating bodies, it is to be expected that  $\beta$  in (1) is not a universal constant. Indeed, different results for  $\beta$  were found for fourteen different rotating bodies: metallic cylinders in the laboratory, moons, planets, stars and galaxies [11]. A mean value for  $\beta$  was found to be  $\beta = 0.076$  [11].

### III. MAGNETARS

Anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) have been discovered in recent years. A pulsed component with a period of a few seconds was present in the radiation, which suggests that the central object is probably a single neutron star, since no sign of a companion was found. An important feature of SGRs is the presence of sporadic bursts of gamma radiation with flare energies up to  $10^{44}$  ergs.

The magnetic fields of these objects, assuming that their deceleration is due to magnetic dipole radiation, are  $\sim 10^{15}$  G, which is three orders of magnitude greater than the fields in radio pulsars. Assuming that the magnetic fields play the determining role in these objects, they form a special group known as magnetars. Magnetars initially rotate with short periods  $\sim 1$  ms, but quickly lose most of their rotational energy through magnetic braking, giving a large energy boost to the associated supernova explosion. The magnetar model was introduced by Duncan and Thompson ([12],[13]).

The recent observation of quasi-periodic oscillations (QPOs) in giant flares in SGRs 1806-20 and 1900+14 may be the first direct detection of neutron star oscillations ([14], [15], [16]). The Alfvén wave crossing time in the neutron star is  $t_A = 2R/V_A \sim 70B_{15}^{-1}\rho_{14}^{1/2}R_6$  ms, where  $B \equiv 10^{15}B_{15}$  G, the density  $\rho \equiv 10^{14}\rho_{14}g/cm^3$ , and  $V_A^2 = B^2/4\pi\rho$ . Glampedakis et al.

([17], [18]) showed that the oscillating modes most likely to be excited by a fractured crust are those for which the crust and core oscillate together due to the coupling of the strong magnetic field,  $B \sim 10^{15}$  G. These global modes are on the order of the pure toroidal crustal modes with frequencies  $\sim 30 - 100$  Hz ([19],[20]).

From eqs. (1)-(3), we obtain the NMGEC prediction for  $B_{nm}$ ,

$$B_{nm} = \beta c^{-1} G^{1/2} I r^{-3} 2\pi P^{-1} G, \quad (4)$$

where  $I$  is in  $g\text{ cm}^2$ ,  $r$  in km, and  $P$  is in seconds. Typical values for  $I$  and  $r$  for neutron stars are  $I = 10^{45}$   $g\text{ cm}^2$  and  $r = 10^6$  cm. When inserted in (4), we obtain

$$B_{nm} = 5.414 \times 10^{13} \beta P^{-1} G. \quad (5)$$

The very intense magnetic fields,  $\sim 10^{15}$  G, in magnetars are not easy to produce astrophysically. We examine the possibility that they could be produced by NMGEC. Using  $P \simeq 1$  ms in (5) for a newly born neutron star, we get  $B \simeq 5 \times 10^{16} \beta$  G. We thus find that NMGEC can easily produce the required fields.

#### IV. QUASARS

Supermassive black holes are generally believed to be the power sources of quasars and other active galactic nuclei. Apart from its mass, the other fundamental properties of an astrophysical black hole are its charge and, in particular, its spin. A spinning Kerr black hole has a greater radiative efficiency than that of a non-rotating Schwarzschild black hole. Both are expected to have negligible charge due to the high conductivity of the surrounding plasma. Wang et al. [21] estimated the average radiative efficiency of a large sample of quasars, selected from the Sloan Digital Sky Survey, by combining their luminosity and their black hole mass functions. They found that quasars have an average radiative efficiency of  $\sim 30\% - 35\%$  over the redshift interval  $0.4 < z < 2.1$ . This strongly suggests that the Kerr black holes are rotating very rapidly with approximately maximum angular momentum, which remains roughly constant with redshift. The inferred large spins and their lack of significant evolution with redshift are in agreement with the predictions of semianalytical models of hierarchical galaxy formation ([22], [23], [21]). In these models, black holes gain most of their mass through accretion.

Using the rotation measures (RMs) of high redshift galaxies, Pentericci et al. [24] obtained an estimate of the accretion disk magnetic field in the region where polarized optical radiation is generated. Assuming that the magnetic flux is conserved and that the optical radiation is emitted from the accretion disk in the region  $\sim 10^3 r_g$ , (where  $r_g$  is the gravitational radius of a supermassive black hole), we obtain the following estimate of the accretion disk magnetic field in the generation region of the optical radiation:

$$B \sim 2 \times 10^3 (RM/10^3)(10^8 M_\odot/M_{BH})^2 G \quad (6)$$

[24]. The field strength given by (6) for quasar accretion disks was found to be  $\sim 150 - 300$  G [24].

We can compare this value with the NMGEC prediction for magnetic fields in quasars. Using (1) and taking  $M_{BH} \sim 10^8 M_\odot$  and  $\beta \sim 1$ , we obtain  $B \sim 10^9$  G near  $r_g$ . Assuming that the magnetic flux produced by NMGEC is conserved as it expands from  $r_g$  to  $10^3 r_g$  (decreasing as  $1/r^2$ ), we obtain  $B \sim 10^3$  G at  $r \sim 10^3 r_g$ , which is in good agreement with the quasar accretion disk magnetic field obtained from (6).

## V. GAMMA-RAY BURSTS

Magnetic fields are very important in Gamma-Ray Bursts (GRBs)[25]. It is generally accepted that the observed afterglow is produced by synchrotron emission which involves magnetic fields. Synchrotron radiation is also the best model for prompt  $\gamma$ -ray emission. The relativistic outflow is a Poynting flux (with negligible baryon content) [25]. A natural way to produce the Poynting flux is by magnetic reconnection.

The magnetic field required for the Poynting flux can easily be evaluated. Since the compact source is of size  $\sim 10^6$  cm, magnetic fields  $\sim 10^{15}$  G are needed to produce the required energy output of the GRB.

We apply equation (1) to a rapidly rotating black hole, assumed to be the inner engine of a popular model of the GRB [25]. The magnetic field in the vicinity of the black hole is obtained, using  $r \sim 10^6$  cm, from (3). The dimensionless spin parameter  $\alpha$  of the GRB is defined as  $Jc/GM^2$ . We then obtain the magnetic field for a GRB in terms of the spin

parameter  $\alpha$  from (1):

$$B = \frac{G^{3/2} M^2 \alpha \beta}{c^2 r^3} \approx 225 \frac{(M/M_\odot)^2}{(r/R_\odot)^3} \alpha \beta \text{ G} \quad (7)$$

The NMGEC prediction from (7), using  $\alpha \sim 1$ ,  $\beta \sim 0.1$ ,  $r \sim 10^6$  cm, and  $M \sim 2.5 M_\odot$  is  $B \sim 10^{15}$  Gauss, in good agreement with the required field.

## VI. CONCLUSIONS AND DISCUSSION

Observations indicate the presence of intense magnetic fields in magnetars, quasars and gamma-ray bursts (GRBs). Standard astrophysical theories have difficulty in explaining them. We evaluated the magnetic fields predicted by non-minimal gravitational-electromagnetic coupling (NMGEC) for these objects. In the magnetar models for AXPs, SGRs, and QPOs, magnetic fields  $\sim 10^{15}$  G are required. We showed that for typical values of moments of inertia, radii, and periods for rapidly rotating newly-born neutron stars, the NMGEC theory predicts the required magnetic fields.

The accretion disk magnetic field in quasars in the region  $\sim 10^3 r_g$ , where polarized optical radiation is generated, is estimated to be on the order of a thousand G. For a maximally rotating black hole in this region, NMGEC predicts this field.

In GRBs a magnetic field  $\sim 10^{15}$  G is required to produce the Poynting flux needed to supply the energy observed. This field is predicted by NMGEC to exist outside a rapidly rotating black hole of several solar mass.

It is not easy to produce astrophysically intense magnetic fields. We showed here that such fields are predicted naturally by rapidly rotating neutron stars and black holes by NMGEC. If such intense fields are definitely proven to exist, it would give support for the NMGEC theory.

## Acknowledgments

R.S.S. thanks the Brazilian agency FAPESP for financial support (04/05961-0). R.O. thanks FAPESP (06/56213-9) and the Brazilian agency CNPq (300414/82-0) for partial support.

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